Bi-Monthly Research Progress Report 1

Contractor's Name: Integran Technologies USA, Inc.

Address: 2541-Appletree Drive, Pittsburgh, PA 15241-2587

Contract Number: DTRT57-08-C-10022

SBIR Topic Number, Title: 07-PH1, Crack Arrest and Structural Repair of High Strength Steel Piping by In-Situ Sleeving of Nanostructured Materials.

Period Covered by the Report: from December 17, 2007 to February 17, 2008

Principal Investigator, Telephone Number, Fax Number, and E-Mail:
Dr. Virgil Provenzano, 301-675-3730, 301-975-4553, vprovenzano@integranusa.com

Classification: N/A

Report Narrative:

The objective of this six month Phase I effort is to establish the technical and economic feasibility of a high strength steel pipeline soft crack arrest (CA) concept based upon the application of high strength, high toughness nanocrystalline metal sleeves to the outer surface of a high strength steel gas pipeline. In order to achieve its objectives, the project is comprised of the following three main activities:

Task 1 – Technology Review: gather industry experts together; evaluate the feasibility of the Nanometal sleeving concept

Task 2 – Lab-scale Proof of Concept – prove that Nanometal can be applied to e.g. X100 steel with high bond strength and resulting in a substantial strengthening effect

Task 3 – Finite Element (FE) Analysis modeling to predict the effectiveness of the Nanometal sleeve as a crack arrestor against high strength steel pipeline running fractures

1.1. Task 1 – Technology Review

The primary thrust of the first two months of this six month SBIR Phase I effort has been to establish the technical and economic feasibility of the Nanometal-based crack arrestor (CA) concept via discussions with experienced pipeline industry personnel very familiar with the large-scale use of gas pipeline crack arrestors. In order to accomplish this objective, an Industry Advisory Group, comprised of both pipeline implementers (BP, TransCanada Pipelines) and pipeline coating experts (BrederoShaw), was assembled to critically evaluate the proposed CA concept. The following are the general conclusions drawn from this feasibility review exercise:

1. Integran's Nanometal sleeve technology appears to be an excellent means to affect *in situ* repair of process piping that is already cracked / corroded. However,

the present project is more concerned with the application of numerous CA sleeves strategically spaced along the length of a gas pipeline in a pre-emptive manner; i.e. before or immediately after pipeline installation. In other words, this project is concerned primarily with the crack arresting capability of the Nanometal sleeve rather than delaying the onset of running fractures in the pipeline. Therefore, consistent with the main objective of the SBIR Phase I solicitation regarding the assessment of novel candidate materials for use as soft crack arrestors and also consistent with the very informative discussion with the gas pipeline industry experts, it was made explicit that the project focus will be centered on assessing the potential of Nanometal sleeving as an effective soft crack arrest tool. Consequently, taking into account the relatively short time available for carrying on this SBIR Phase I effort (six month duration) as well as its level of effort ($100k project), in the current project we will be unable to examine the characteristics of Nanometal sleeving with respect to its unique "crack bridging" and "*in situ* structural reinforcement of degraded sections of critical process piping" for which the technology has been successfully demonstrated by Integran to be a very effective repair method for degraded process tubing. It is hoped, therefore, that the potential of the Nanometal sleeving as a versatile and a cost-effective *in-situ* repair method for repairing corroded or damaged sections of gas pipelines will be an important component of a larger follow-on Phase II effort to the present Phase I project.

2. Regardless, the fact remains that application of high strength, high toughness material to the outer surface of pipeline steel is the best way to stop a running fracture. We therefore expect that the Nanometal sleeving material would be an effective crack arrestor material because of its intrinsically high strength and toughness. This then prompts the following key question that is central to establishing the overall feasibility of the proposed concept:

What thickness of Nanometal is required to arrest a running fracture?

The members of the pipeline Industry Advisory Group deemed this question to be of paramount importance for two main reasons:

1. Since the concept is based upon electrodeposition whereby Nanometal is deposited layer upon layer onto the substrate surface, a thin coating of Nanometal (<2-5 mm) can be applied with ease in a relatively short period of time (<24hrs), whereas the application of 5mm+ may be more challenging from a technical level-of-difficulty and processing time perspective
2. As a direct result of the time required to build thick layers of Nanoplate, the application of thick (>5 mm = 24hrs+) Ni-based Nanometal sleeves would likely be far more costly compared to the incumbent CA technologies, namely a) composite-based CA's and b) the application of an additional layer of pipeline steel to simply double wall thickness. On the other hand, thin (<5 mm thickness) Nanometal sleeves could prove attractive, especially if the sleeve performance with respect to "soft"

crack arrest behavior turns out to be compelling. Both incumbent CA concepts cost less than $15k/sleeve. We do not know how much more end users would be willing to pay for a CA that stops running fractures in a "soft" manner (the goal of this project).

Primary recommendation of the Industry Advisory Group

To summarize, the time required to apply the Nanometal-based CA is directly proportional to the Nanometal thickness required to arrest a running fracture. Both the practical and economic feasibility of the concept seem to be predicated upon the establishment of an estimated thickness value for the Nanometal sleeve. It is therefore clear that a rough estimate of the Nanometal thickness should be made ASAP and so the Industry Advisory Group has suggested that the Task 3 activity (Finite Element (FE) modeling of crack arrest effectiveness) be carried out before or concurrent to the Task 2 – Laboratory Proof of Concept work.

3. The third conclusion drawn from the Industry Advisory Group discussions is that the unique features of the Nanometal-based concept that could have a significant impact on the CA effectiveness and/or mechanics of crack arrest (i.e. "soft" vs "hard" arrest) will be difficult to prove out within the auspices of this Phase I:
    - Excellent Nanometal bond strength to the high strength steel = more efficient crack energy dissipation / distribution?
    - Ability to <u>grade</u> the Nanometal sleeve thickness i.e. apply a "bell shape" in cross section with a thick central section tapering thinner near the sleeve edge – may impact "hard" vs "soft" crack propagation
    - Ability to apply Nanometal with an intrinsic compressive stress to "squeeze" the steel pipe – may impact mechanics of sleeve crack arrest

    Unfortunately, it is the opinion of the Industry Advisory Group that the impact of these novel features on CA effectiveness and the potential to promote "soft" vs "hard" CA can only be borne out through large-scale burst tests, which are beyond the scope of this Phase I project. In other words, it seems unlikely that we will be able to demonstrate the CA impact of these compelling features of the concept until a later stage of development unless it can be built into the Phase I Task 3 FE Analyses somehow. Initial appraisals of the level of sophistication of existing high strength steel pipeline crack arrest modeling tools (e.g. CSM in Italy) do not appear to support this capability, however (more on this in Section 1.3 below).

Impact of the Industry Advisory Group discussions on the Phase I Project Plan:

1. Recognition that overall feasibility is linked to the establishment of an estimated Nanometal thickness required to stop a running crack = initiate Task 3 ASAP
2. Recognition that many of the novel features of the concept as it pertains specifically to the mechanics of "hard" vs "soft" crack arrest (superior sleeve bond strength, potential to grade Nanometal sleeve thickness, ability to apply high strength Nanometal with "squeezing" compressive stress) will be very difficult to prove out because large-scale burst tests are beyond the scope of this Phase I

effort. Conclusion: find out what would be required to explore these "soft" arrest possibilities via FE analyses (lead-in from Task 3)

3. Task 1 complete and deemed exceptionally valuable. Now shift overall project emphasis towards Task 3 (see Project Future Activities below)

1.2. Task 2 – Laboratory Proof of Concept

Given the emphasis shift to Task 3 FE analyses described above, we believe Task 2 should be delayed until the latter half of the Phase I program. In other words, it makes better sense to establish the overall project feasibility with respect to CA effectiveness and economic feasibility before fabricating and tensile testing the Proof of Concept samples. Nevertheless, in advance of the Task 2 work, we have identified a source of X100 pipeline steel (TransCanada Pipelines) through our Industry Advisory Group activities so that we can have the material on hand and prepared in order to complete Task 2 before the end of Phase I. Another reason it makes sense to delay the onset of Task 2 is because the FE analyses will provide a target Nanometal thickness value that should then be used for all subsequent Task 2 specimen preparation activities.

1.3. Task 3 – Finite Element (FE) Analyses

As outlined in Section 1.1, the Industry Advisory Group discussions were extremely helpful insofar as they assisted us in clarifying what would be required to make a Nanometal-based crack arrestor feasible from a practical and economic perspective, and this is linked primarily to sleeve thickness. To this end, preliminary conversations with an acknowledged world leader (Centro Sviluppo Materiali s.p.a. (CSM)) in the field of high strength pipeline steel crack arrestor modeling have been conducted. While we have not yet come to terms on the specifics of the working arrangement, CSM appears willing to work with Integran on the Task 3 activity.

In general, what CSM has communicated to us is the following:

1. The mechanics of running fracture crack arrest are relatively complex and their model does not have the capability to vary sleeve bond strength, thickness grading, or intrinsic compressive stress.
2. CSM would be willing to do development work on the code to incorporate this increased level of complexity [great idea but probably not realistic for this Phase I]
3. CSM could instead run the code in its present form with its current limitations in an attempt to establish a Nanometal CA sleeve thickness estimate [recommended course of action]
4. CSM would be willing to work with us within the general framework of a DoT contract, should DoT choose to pursue the concept further

Project Future Activities:

The following are our plans for the final 4 months of the 6 month SBIR Phase I project:

1. Initiate Task 3 ASAP: come to terms with CSM on an agreement to run their pipeline crack arrest simulations "as is" without any code modifications.
2. Obtain estimate of Nanometal thickness required to arrest a running fracture
3. Estimate level of technical difficulty, process time required, and overall cost of applying a Nanometal CA sleeve on the basis of the Nanometal sleeve thickness estimate outputted from FE
4. Obtain and prepare X100 material so that Task 2 can be carried out upon completion of the aforementioned activities and before the end of Phase I

Industry Advisory Group Members:

1. Fraser King, Integrity Corrosion Consulting Ltd. (advisor to Integran and link to pipeline industry personnel)
2. David Horsley, BP (pipeline / CA implementer)
3. Millan Sen, TransCanada Pipelines (pipeline / CA implementer)
4. Peter Singh, BrederoShaw (pipeline coater)